Was the Himalayan orogen a climatically significant coupled source and sink for atmospheric CO_2 during the Cenozoic?

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Abstract

The hypothesis that the Himalayan orogen was a climatically significant coupled source and sink for atmospheric CO_2 during the Cenozoic is evaluated in light of the timing, duration and CO_2 fluxes associated with Himalayan metamorphism and chemical weathering. We suggest that diachronous Eohimalayan metamorphism occurred over a $\sim$20 m.y. time span (Middle Eocene to Early Oligocene) with total metamorphic CO_2 production of $\sim$4–10 $\times$ 10^{18} mol. Because this is much greater than the amount of carbon stored in the atmosphere and oceans, and because uplift and accelerated erosion began at least $\sim$5 m.y. after the peak of metamorphism, we conclude that it is implausible that CO_2 produced by metamorphism in the Himalayan orogen was consumed millions of years later by erosion-enhanced weathering in this orogen. Assuming a global climate/silicate-weathering feedback, we estimate that metamorphic CO_2 degassing from the Himalayan orogen would have produced a warming of <0.5ºC, and enhanced weathering in this orogen would have produced a cooling of <0.2ºC; thus, direct climate effects of this degassing and weathering were likely to have been minor. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Bickle [1,2] attributed the 50–100 m.y. episodicity in the seawater $^{87}Sr/^{86}Sr$ curve to the episodic nature of collisional orogenesis. He hypothesized that, for each cycle, CO_2 added to the atmosphere from post-collisional regional metamorphism was consumed by enhanced chemical weathering accompanying subsequent uplift and erosion.

For the Himalayan orogen Bickle [1] concluded

that a 50% linear increase in CO_2 drawdown by silicate weathering over the past 40 m.y. consumed 13–26 $\times$ 10^{18} mol of CO_2. His computed metamorphic CO_2 release of 24–60 $\times$ 10^{18} mol during Himalayan regional metamorphism more than compensated for the consumption of atmospheric CO_2 by chemical weathering.

Bickle [1,2] concluded that imbalances of ±25% in the CO_2 degassing vs. weathering fluxes were implied by the seawater Sr-isotope curve. However, quantitative modeling of the global carbon cycle [3–6] illustrates that CO_2 degassing and weathering fluxes for time periods > 1 m.y. must be well within

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±25%. Thus, for a silicate weathering CO_2 flux of 8×10^{18} mol m.y.$^{-1}$ [6], imbalances between Earth degassing fluxes and silicate-rock weathering fluxes must have been $<2 \times 10^{18}$ mol m.y.$^{-1}$ (cf. Bickle [1]).

Here we assess the validity of the hypothesis that CO_2 added to the atmosphere by Himalayan metamorphic degassing was consumed by chemical weathering in this orogen. We quantify imbalances in CO_2 sources and sinks associated with the Himalayan orogen through estimates of the timing and rates of metamorphic CO_2 degassing and CO_2 drawdown by silicate weathering, and to compare these imbalances with estimates of maximum plausible imbalances inferred from paleoatmospheric CO_2 levels during the Cenozoic.

2. Constraints on maximum Cenozoic atmospheric CO_2 content

Freeman and Hayes [7] concluded that the maximum atmospheric CO_2 contents in the Cenozoic were about twice the modern value, with significant uncertainties [5,8]. Maximum atmospheric CO_2 contents of 1300 ppm have been estimated for the Late Cretaceous [9]. Because the atmospheric CO_2 levels of the Cenozoic were lower than the Cretaceous [7,10], we adopt ∼1000 ppm as an upper limit for Cenozoic atmospheric CO_2 concentration.

3. Computational strategy

We constrain maximum values of the imbalance in atmospheric CO_2 input vs. output consistent with estimated Cenozoic atmospheric CO_2 levels. We use a simple model of ocean chemistry and air–sea gas fluxes [6] to estimate the changes in atmospheric CO_2 content resulting from inferred CO_2 fluxes associated with the Himalayan orogen, in the absence of other negative stabilizing feedbacks, such as the climate/silicate-weathering feedback [3,4,6,11]. If, as we demonstrate, the inferred change of atmospheric CO_2 content resulting from Himalaya-related CO_2 fluxes are implausible, this strongly suggests that the proposed coupling between metamorphic degassing and orogenically induced weathering within the Himalayan orogen was insufficient to maintain

global balance in the carbon cycle, and that global climate/silicate-weathering feedback maintained a near-balance between atmospheric inputs and outputs of CO_2.

3.1. Quantifying effect of degassing/weathering imbalances

To quantify the effect of imbalances between CO_2 degassing and silicate-rock weathering on ocean chemistry and atmospheric pCO_2 we used the ocean–atmosphere model of Berner and Caldeira [6]. The essential assumptions are: the ocean consists of deep and surface reservoirs of carbon and alkalinity, the atmosphere is a single reservoir of carbon; the surface ocean is in equilibrium with atmospheric CO_2; and the deep-ocean is in equilibrium with calcite. Our basic computational approach is to add carbon from excess degassing or alkalinity from excess weathering and let (1) CO_2 in the atmosphere equilibrate with the surface ocean, (2) the carbon and alkalinity in the surface ocean equilibrate with that of the deep-ocean, (3) carbon and alkalinity in the deep-ocean equilibrate with calcite in marine sediments, and (4) the surface- to deep-ocean gradients of total dissolved inorganic carbon and total alkalinity remain constant. In the case of excess degassing, equilibration with sediments involves carbonate dissolution, whereas with excess weathering, equilibration with sediments involves carbonate precipitation. As this equilibration process approaches steady state, we track atmospheric pCO_2.

Carbonate chemistry was computed using the equations and rate constants described in Stumm and Morgan [12], assuming a deep-ocean temperature of 2ºC and the surface ocean at a temperature of 18ºC and with a salinity of 35‰. The carbonate-ion concentration of the deep-ocean is a function of deep-ocean total dissolved inorganic carbon and alkalinity:

$$\left[CO_3^{2-} \right]_{deep} = CO_3 \left(\left[\sum CO_2 \right]_{deep}, \quad \left[\sum Alk \right]_{deep} \right)$$

(1)

The system is solved assuming $[CO_3^{2-}]_{deep} = 90$ μmol kg^{-1}. Surface total dissolved inorganic carbon and alkalinity concentrations differ from the deep-ocean values due to both marine biology and chemical solubility [13]. Here, we consider the dif-

ference between surface values and deep value to be constant:

$$\left[\sum CO_2\right]_{surface} = \left[\sum CO_2\right]_{deep} - \Delta\left[\sum CO_2\right] \quad (2)$$

and

$$\left[\sum Alk\right]_{surface} = \left[\sum Alk\right]_{deep} - \Delta\left[\sum Alk\right] \quad (3)$$

where $\Delta\left[\sum CO_2\right] = 290\ \mu mol\ kg^{-1}$ and $\Delta\left[\sum Alk\right] = 92\ \mu eq\ kg^{-1}$ [13]. Surface pCO_2 is computed based on surface total dissolved carbon and alkalinity concentrations as per Stumm and Morgan [12]:

$$pCO_{2,\ surface}$$
$$= pCO2\left(\left[\sum CO_2\right]_{surface},\ \left[\sum Alk\right]_{surface}\right) \quad (4)$$

The simplified model is intended to represent gross features of ocean chemistry that are important to the problem at hand. Results would be qualitatively similar with other reasonable assumptions. For example, the deep-ocean carbonate-ion concentration could have been determined by a flux constraint on alkalinity instead of making the assumption of constant carbonate-ion concentration. Over the course of the Cenozoic, the calcite compensation depth (CCD) was no more than ~1 km shallower than today [14]. At constant temperature and calcium-ion concentration, a 1 km shallowing of the calcite lysocline would imply a ~15% reduction in the carbonate-ion concentration [15]. Using the equations in Stumm and Morgan [12], we compute that at constant pH, this change in the CCD depth would correspond to a proportional reduction in atmospheric CO_2 content. In contrast, at constant total alkalinity this CCD depth change would imply a ~25% increase in atmospheric CO_2 content. Uncertainties of this magnitude would not affect our conclusions.

3.2. Quantifying effect of changes in atmospheric CO_2 from degassing and weathering

To quantify the effect of imbalances in CO_2 degassing and weathering on atmospheric CO_2 content, we apply the computed amount of excess CO_2 (or alkalinity, in the case of excess weathering) to the model described above and in [6]. Sundquist [3] provided an analysis of the global response to 10%

imbalances in fluxes of CO_2 degassing vs. CO_2 drawdown by weathering. He found that if the silicate-weathering feedback acted as has been proposed, that the time-scale to approach a new steady-state atmospheric CO_2 content is ~300,000–400,000 year.

4. Himalayan metamorphism

4.1. Timing and duration of metamorphism

Analysis of the timing and duration of Himalayan metamorphism is necessary to estimate the rate of CO_2 degassing and to assess the temporal link between CO_2 degassing and atmospheric CO_2 drawdown by chemical weathering. Bickle [1] proposed such a temporal link, but did not carry out an assessment of the timing of the degassing or the plausibility of the time lag between enhanced degassing and enhanced weathering.

Cenozoic regional metamorphism in the Himalaya is manifest in the High Himalayan Crystalline Series (HHCS). Radiometric dating [16–18] of the HHCS in central Nepal suggests two periods of metamorphism: Barrovian-type prograde Eohimalayan metamorphism followed by retrograde Neohimalayan metamorphism.

4.1.1. Eohimalayan prograde metamorphism
Timing of the initiation of prograde metamorphism is constrained by the age of collision. Due to counterclockwise rotation of the Indian plate, collision in the Himalayan orogen was diachronous: ~52 Ma in the west and ~41 Ma in the east [19]. Diachroneity of the India–Asia collision would have resulted in a corresponding eastward propagation of post-collisional metamorphism in the Himalayan belt. Based on geochronologic data Guillot et al. [18] concluded that the Eohimalayan metamorphism occurred in the Mid-Eocene to Early Oligocene in the western part of the orogen and Late Oligocene in the eastern part. However, recent geochronologic data suggest that the prograde metamorphism in the western part of the belt could have continued into the Late Oligocene [20].

4.1.2. Neohimalayan retrograde metamorphism
In the central Himalaya (Nepal), Neohimalayan metamorphism occurred from Late Oligocene

through Middle Miocene [16,17]. The Neohimalayan event was accompanied by brittle deformation and fluid circulation along the Main Central Thrust [16]. Widespread shallow metamorphic CO_2 degassing *could* have accompanied extensional tectonism throughout the Neohimalayan metamorphism [11]. As with the Eohimalayan metamorphism, diachronous collision would have resulted in the eastward propagation of the Neohimalayan metamorphism.

4.2. Metamorphic CO_2 degassing

To compute the total CO_2 evolved during Himalayan metamorphism, Bickle [1] inferred a value of 5×10^7 km^3 for the total volume of rock that underwent metamorphism from the volume and composition of sediment in the Himalayan foreland basins and submarine fans [21]. He derived the amount of CO_2 released by metamorphism in two ways: (1) $\sim 60 \times 10^{18}$ mol, computed by arbitrarily assuming that the protolith contained 5 wt% carbonate and implicitly assuming that this carbonate was completely consumed by metamorphic decarbonation (termed the 'mass loss' method [11]), and (2) 24×10^{18} mol, computed using an average fluid flux during metamorphism of 10^3 m^3 m^{-2}, arbitrarily assuming a 10 km path length for fluid flow, and an estimated fluid composition of 10 mol% CO_2.

Johnson's [22] more conservative estimate of eroded volume (2×10^7 km^3) would reduce Bickle's total estimated CO_2 production from 24 to 60×10^{18} to 10 to 24×10^{18} mol. Bickle's computations implicitly assume that the sediment contained in the foreland basins and the Indus and Ganges–Brahmaputra fans was entirely derived from the HHCS; however, up to 20% of the Bengal Fan detritus in the past 20 m.y. may have been derived from erosion of other units [23]. This factor would further reduce Bickle's [1] estimated CO_2 loss to 8 to 19×10^{18} mol.

Rather than using the volume of sediment in the Himalayan foreland basins and Bengal fans, we derived a more conservative volume of rock undergoing Himalayan metamorphism by considering the exposed $\sim 2.5 \times 10^5$ km^2 outcrop area of the HHCS [11]. Assuming that ~ 35 km of overburden was removed by erosion [22], the total volume of HHCS removed would be $\sim 9 \times 10^6$ km^3. Bickle's

[1] assumption that the Himalayan metamorphism involved mostly pelitic protoliths is supported by the predominance of metapelites in the HHCS of central Nepal [16]. Assuming that the HHCS protolith was a pelite with 5 wt% CO_2 [1] and that all carbonate was consumed during metamorphism [11], the total amount of CO_2 released during metamorphism of the HHCS computed by the mass loss method would be $\sim 11 \times 10^{18}$ mol. Alternatively, if we apply our estimated CO_2 flux of $\sim 1.5 \times 10^{12}$ mol km^{-2} Ma^{-1} [11] to the $\sim 2.5 \times 10^5$ km^2 exposure of the HHCS, and assume that prograde metamorphism lasted 10 m.y., the total CO_2 flux would be $\sim 3.75 \times 10^{18}$ mol.

Based on estimating CO_2 evolved by mass loss and by fluid flux data, we conclude that the Himalayan orogen would have generated a total of ~ 4 to 11×10^{18} mol of CO_2; approximately one-sixth the amount estimated by Bickle [1]. Our estimate of CO_2 release is less than that of Bickle because we estimated a smaller volume of rock that underwent metamorphism.

Bickle [1] implicitly assumed that all of the metamorphic CO_2 generated at depth escaped to the Earth's surface. However, the CO_2 content of fluids generated by metamorphism at depth would be diminished by precipitation of carbonate upon cooling and decompression of fluids rising toward the Earth's surface [11,24,25]. Although we cannot quantify the amount of CO_2 consumed by carbonate vein formation during the Himalayan metamorphism, we note that carbonate veins occur in metamorphic rocks of the Nanga Parbat area [26]. Thus, some CO_2 was consumed by carbonate vein formation in the Himalayan metamorphic system. As evidenced by massive carbonate formation in major shear zones associated with regional metamorphic belts (such as the Mother Lode system [24]), a significant fraction of deeply generated metamorphic CO_2 could be sequestered upon transport toward the Earth's surface.

Appreciable metamorphic CO_2 could have been released to the atmosphere during extensional tectonism accompanying uplift of the Himalaya [11]. Decarbonation driven by convective circulation of meteoric water in extensional regimes is restricted to the upper ~ 7 km of the crust above the brittle/ductile transition [11]. If the Neohimalayan event was contemporaneous with rapid erosion, the upper ~ 7 km of crust undergoing such devolatilization would

have migrated through the underlying HHCS as the Earth's surface was denuded by erosion. Assuming that 35 km of rock was removed from the Himalayan belt by erosion in the past 20 m.y. [22], the average erosion rate would be 1.75 km m.y.$^{-1}$. Coupling this with the assumption that Neohimalayan decarbonation occurred from ~23 Ma (the start of uplift) to ~13 Ma (muscovite cooling ages), ~17.5 km of the HHCS would have been eroded during this time period. With the exposed surface area of HHCS (~2.5×10^5 km^2) the total volume of HHCS subjected to Neohimalayan metamorphism would be ~4.4×10^6 km^3. If the original protolith had 5 wt% carbonate, ~5.3×10^{18} mol of CO_2 would have been released. However, the CO_2 evolved during the Neohimalayan event was likely to have been far less than this because it is probable that most of the carbonate in the HHCS protolith was consumed by decarbonation during the earlier Eohimalayan prograde metamorphism.

5. CO_2 degassing from Cenozoic Himalayan magmatism

Could Cenozoic magmatism within the Himalaya and Tibetan Plateau have been a climatically significant source of CO_2? As evidenced by batholiths along the Himalayan orogen, widespread calc-alkaline magmatism occurred prior to collision [27]. During decompression at the onset of rapid exhumation, small volumes of leucogranite formed ~20 Ma. Consequently, it is unlikely that the Himalayan belt degassed significant quantities of magmatic CO_2 to the Cenozoic atmosphere. In the Tibetan plateau there was virtually no magmatic activity between 90 Ma and Mid-Miocene [27]. Small volumes of potassic basalts have been erupting in the Tibetan plateau for the past 13 m.y. [27]. Considering the limited solubility of CO_2 in basaltic magmas [28], a climatically insignificant quantity of CO_2 would have degassed from the small volume of Neogene potassic volcanics in the Tibetan plateau. We conclude that the Himalayan–Tibetan magmatism was not a significant source of magmatic CO_2 to the Cenozoic atmosphere.

6. CO_2 drawdown by Cenozoic Himalayan weathering

Bickle [1] and Tajika [29] computed atmospheric CO_2 drawdown fluxes for the past 40 m.y. based on the assumption that the rise in seawater $^{87}Sr/^{86}Sr$ ratios during this time period was produced by enhancement of riverine radiogenic Sr contents by chemical weathering of ^{87}Sr-enriched silicates in the Himalayan metamorphic source rocks. However, coupling the major Sr sources with mass balance computations, the Sr isotopic evolution of the oceans requires that only 20% of the riverine Sr is derived from silicate weathering [30,31]. For the Himalaya orogen this conclusion is supported by Blum et al. [26] who, in a study of a watershed in the HHCS, concluded that 82% of the riverine HCO_3^- flux is from weathering of carbonate and only 18% from silicate weathering. Even though carbonate composes only a small (~1%) proportion of the bedrock exposed in this watershed, it has a dominant effect on the dissolved riverine flux. Furthermore, Sr-isotopic compositions of carbonates in paleosols of the Himalayan foreland basin suggest that the marked increase in Himalayan riverine $^{87}Sr/^{86}Sr$ ratios in the Late Miocene can be attributed to widespread unroofing of highly radiogenic metacarbonate rocks [32]. Based on independent lines of evidence, Quade et al. [32] and Blum et al. [26] concluded that attributing the rise in seawater $^{87}Sr/^{86}Sr$ ratios over the past 40 m.y. to silicate weathering alone results in overestimating the amount of CO_2 consumed. Accordingly, the increased atmospheric CO_2 consumption in the past 40 m.y. would be significantly lower than that computed by Bickle [1].

Himalayan orogenic detritus first appeared in the Early Miocene [33–35]. Thus, enhanced chemical weathering from uplift of the Himalayan belt would have been confined to the past 23 m.y. rather than the past 40 m.y. as inferred from the Sr-isotopic record. Unroofing of radiogenic carbonates from the Himalayan metamorphic belt in the Early Miocene could have contributed to the apparent increase in the seawater $^{87}Sr/^{86}Sr$ during the Early Miocene.

Assuming that enhanced CO_2 drawdown by Himalayan weathering began ~23 Ma, an uncompensated weathering-induced Himalayan CO_2 drawdown flux of 0.064×10^{12} mol yr^{-1} [36] would

have reduced atmospheric CO_2 levels to well below pre-anthropogenic levels (Fig. 2). If Cenozoic atmospheric CO_2 contents were similar to present levels [37], this uncompensated drawdown flux would have depleted atmospheric CO_2 within a few million years.

7. Discussion

If 4 to 11×10^{18} mol of CO_2 were released by diachronous Eohimalayan metamorphism over a 20 m.y. period, and if all of this CO_2 was expelled at a constant rate to the surface, the resulting yearly flux would be ~0.2 to 0.5×10^{12} mol. If not compensated by other mechanisms, degassing fluxes $\epsilon 0.1 \times 10^{12}$ mol yr^{-1} would generate atmospheric CO_2 equivalent to the maximum amount estimated for the Cenozoic (~1000 ppm) within ~5 m.y. of the beginning of regional metamorphism in the Middle Eocene (Fig. 1). Using Bickle's [1] estimated total CO_2 degassing flux (24 to 60×10^{18} mol), atmospheric
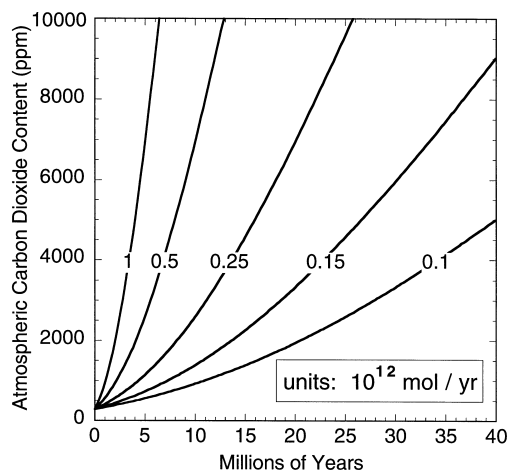

Fig. 1. Change in atmospheric CO_2 concentration (ppm) with selected values of excess CO_2 degassing, barring any compensating feedback mechanisms. The excess CO_2 fluxes are in units of 10^{12} mol yr^{-1}. The initial atmospheric CO_2 content is taken as the pre-industrial value (280 ppm). Excess CO_2 degassing fluxes much greater than 0.1×10^{12} mol yr^{-1} cannot be sustained for many millions of years without generating unrealistic atmospheric CO_2 contents. Therefore, some feedback process, such as increased CO_2 consumption by silicate rock weathering rate with increased global mean temperature, must act to balance the carbon cycle on long time scales [3,4,6].

CO_2 levels of ~1000 ppm would have been attained within 1 m.y. from the start of metamorphism. Because major uplift and erosion of the Himalayan orogen began in the Early Miocene (a minimum of ~5 m.y. after the peak of the Eohimalayan prograde metamorphism), the tectonically induced Neogene chemical weathering in the Himalaya could not have been a sink for this CO_2. Because the Himalayan region was probably an area of subdued topography throughout most of the Oligocene [38], this region would not have been a locus of intense chemical weathering during this period. Consequently, with a climate/silicate-weathering feedback mechanism [4], atmospheric CO_2 generated by Himalayan metamorphism would have been consumed by chemical weathering primarily in areas other than the Himalaya. Using a weathering-rate formulation such as that used by Berner [8], an increase in CO_2 flux of 0.5×10^{12} mol yr^{-1} would produce a warming of <0.5°C [25].

CO_2 drawdown by silicate weathering in the Ganges–Brahmaputra drainage basin is $\sim1.3\%$ of the global total [36]. When scaled to area, this flux is near the world average; thus, the Himalayan system is not an anomalous sink for atmospheric CO_2 [39]. Nevertheless, greenhouse cooling in the late Cenozoic requires that the rate of atmospheric CO_2 drawdown by enhanced chemical weathering was slightly larger than the flux of enhanced CO_2 degassing during this period [40].

Because atmospheric CO_2 drawdown of 0.064×10^{12} mol yr^{-1} from enhanced chemical weathering in the Himalayan system between 23 Ma [39] and the present would have decreased atmospheric pCO_2 to well below pre-anthropogenic levels (Fig. 2), a feedback mechanism that would act to control atmospheric CO_2 content is required. Simultaneous CO_2 drawdown by chemical weathering in other orogenic regions of high relief would have compounded this problem. For example, rapid uplift in the central Andes began ~20 Ma [41]. Because CO_2 consumption by chemical weathering in the Andes/Congo system is larger than that of the Himalayan system [36], the combined chemical weathering CO_2 consumption of the Andes/Congo and Himalaya systems is likely to exceed 0.15×10^{12} mol yr^{-1}. If not compensated, such fluxes would have consumed atmospheric CO_2 well within 10 m.y. after
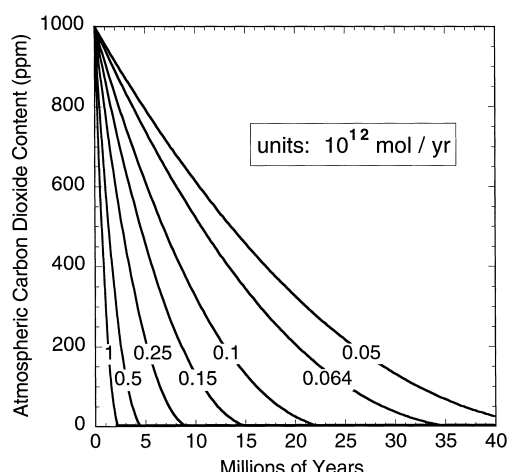
Fig. 2. Change in atmospheric CO_2 concentration (ppm) with selected values of excess atmospheric CO_2 drawdown by chemical weathering, in the absence of compensating feedback mechanisms. The excess CO_2 fluxes (inset) are in units of 10^{12} mol yr^{-1}. The curve for 0.064×10^{12} mol yr^{-1} is based on Galy and France-Lanords [36] estimate of long-term drawdown of atmospheric CO_2 by silicate weathering in the Ganges–Brahmaputra drainage basin. The initial atmospheric CO_2 content (1000 ppm) is the maximum value estimated for the Cenozoic (see text). If uncompensated, CO_2 consumption by silicate weathering cannot be sustained for many millions of years without generating unrealistic atmospheric CO_2 contents. Therefore, some feedback process, such as diminished CO_2 consumption by silicate rock weathering rate with cooler global mean temperatures, or enhanced Earth degassing, must act to balance the carbon cycle on long time scales [3,4,6].

the beginning of the Neogene (Fig. 2). As CO_2 was removed from the atmosphere, the Earth would have cooled and the hydrologic cycle would have decelerated, leading to diminished silicate-rock weathering in other areas [29,42]. Enhanced burial of organic carbon may have been a significant additional sink for atmospheric CO_2 during the Neogene [39]. Using the model described in Kerrick and Caldeira [11] we compute that a regionally enhanced weathering flux of 0.064×10^{12} mol yr^{-1} of CO_2 would diminish atmospheric CO_2 content by ~4%, cooling the Earth by <0.2°C. This cooling would occur on the time-scale of 300,000–400,000 year [3], and would be sufficient to lower weathering rates elsewhere to compensate for enhanced Himalayan weathering.

Enhanced magma production at mid-ocean ridges and back-arc basins within the past 10 m.y. [43], coupled with anomalously high CO_2 fluxes from

volcanic [44] and non-volcanic [45] sources, could also have provided additional sources of atmospheric CO_2 during the last half of the Neogene. Increase in the amount of subducted pelagic carbonate throughout the Cenozoic, and consequent expulsion of the CO_2 into the atmosphere by arc volcanism [29,46], could also have provided additional CO_2 to the atmosphere. In contrast to a model of removal of atmospheric CO_2 by subduction of carbonate [47], arc magmatism may return of subducted CO_2 to the atmosphere [11]. Furthermore, CO_2 degassing from other magmatic regimes could have had an influence on Cenozoic paleoclimate. For example, the apparent diminution in global temperatures in the early Cenozoic may reflect diminished global magmatic CO_2 expulsion as evidenced by the marked decline in the total volume of mid-ocean ridge and flood basalts during the early Cenozoic [11].

8. Conclusions

Relatively minor imbalances in the rates of input and output of atmospheric CO_2 on time-scales >1 m.y. can produce rather large changes in atmospheric CO_2 content. For example, an imbalance of ~2% between CO_2 sources and sinks, sustained over 10 m.y., would be sufficient to produce unrealistic Cenozoic atmospheric CO_2 contents (Figs. 1 and 2). Metamorphic and magmatic degassing are insufficiently coupled to the tectonic and lithologic factors affecting weathering rates for this link to provide a feedback between CO_2 degassing and CO_2 consumption by silicate weathering. Therefore, some feedback must maintain this close balance; this feedback must depend on atmosphere or ocean carbon content [4]. Taking the proposed global climate/silicate-weathering feedback into account [8], relatively minor variations in CO_2 degassing or silicate-rock weathering have a relatively modest impact on global climate.

Our primary conclusions are: (1) because of the long time lag (>5 m.y.) between Eohimalayan metamorphism and enhanced chemical weathering, and the limited capacity of the ocean–atmosphere system to store carbon, the Himalayan orogen was not a coupled source and sink for atmospheric CO_2 during the Cenozoic; (2) in the absence of a negative

feedback, computed Eohimalayan metamorphic CO_2 degassing fluxes would have exceeded the maximum estimated atmospheric CO_2 contents for the Cenozoic within 5 m.y.; (3) without a negative feedback, an estimated atmospheric CO_2 drawdown from enhanced Neogene Himalayan chemical weathering would have produced atmospheric CO_2 contents well below the estimated pre-anthropogenic levels; (4) because these atmospheric CO_2 contents are implausible, a negative feedback mechanism such as the proposed climate/silicate-weathering feedback must function to closely balance atmospheric CO_2 sources and sinks; and (5) due to the global climate/silicate-weathering feedback, CO_2 produced in the Himalayan orogen was likely consumed within a few hundred thousand years by enhanced silicate weathering in other regions of the world.

Acknowledgements

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